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Model-Free Control of Shape Memory Alloys Antagonistic Actuators [★]

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Abstract: This paper deals with a first application of the new framework of model-free control to the promising technology of shape memory alloys actuators. In particular antagonistic shape memory alloys actuator. These devices are known to be difficult to model in a control perspective. Simulations results are exposed and some preliminary experimental results illustrates the paper.

Keywords: Nonlinear control design; Robust nonlinear control; Intelligent controllers; Microactuators; Mechatronic systems

1. INTRODUCTION

Shape memory alloys (SMA) offer the possibility to recover a known shape after a thermomechanical cycle. This property, known as the shape memory effect, is due to the transition between the two crystallographic phases they are composed. This variation of shape, controlled by temperature variation, may be used in the development of actuators, see Peirs et al. [2002] and Kohl et al. [2002]. These materials permit to simplify the mechanism, to reduce the size of actuators and to apply force without significant motion, see De Sars [2005]. SMA can easily be heated by Joule effect, but their control remains a problem and it is principally due to the complexity of their hysteretic behaviour, see Patoor et al. [1994]. A second difficulty is that the characteristics of the material are time-varying, especially during cyclic loadings. Phases

kinetic transformations and 3-dimensional models are proposed in Leclerc and LExcellent [1996], Sittner et al. [2000], Arbab Chirani et al. [2003] and Bouvet et al. [2004]. These complex models can render very subtle properties of SMA, but often need to compute a finite element code, what is not suitable for control. On the opposite side, Robotics research have been done on SMA actuator by using simpler model and classical control method. Classical PID loop are used in Calin et al. [1997], Shameli et al. [2005] and Da Silva [2007]. A feedforward path is added in Majima et al. [2001]; the feedforward command is obtained by using a Preisach model for modelling the hysteretic effect. In Dutta et al. [2005] feedforward scheme is also used but the hysteretic behaviour is described by a Duhem differential hysteresis model. Passivity property of the system is used in Madill and Wang [1998] to prove stability of a proposed proportional law. Nonlinear control techniques based on the Lie algebra are also used in Benzaoui et al. [1999]. Even if their model are quite good enough, using a dynamic model for computing the control law, need firstly to identify the model parameter. As we have already mention the

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model parameter of SMA vary during cycling, then a classical model based control is ineffective or particularly complex. We report our experience, where industrial partners still explain that in order to realise the process control, the part of process modelling, represents 90 % of project global time. Indeed, to define the physical model structure, to identify unknowns parameters, to collect experimental data, to valid the model are never simple. However, how is it possible to control a complex process without any model?

In this paper, a solution to this difficult problem is proposed. The proposition is based on some new results in this framework (Fliess et al. [2006b,a], Join et al. [2006]). The approach uses a derivative estimation (see, Mboup et al. [2007], Fliess et al. [2007]) which provides a good results even if signal are corrupted by noise. Thus a non-physical model valid a very short part of time is estimated and permits classical control design.

Some simulations highlight the advantages of the proposed method. To this end, several perturbation types are simulated. This is particularly clear in case of SMA, where model complexity is detailed.

The paper is organised as follows: The next Section is a short review and introduction to the new “Model-free control” and explains the design of a control law with this new framework; Sec. 3 develops the model-free control of a shape memory alloys actuator and gives simulation results. Sec. 4 concludes the paper and raises some perspectives.

2. MODEL FREE CONTROL

Model free control is a very recent approach to nonlinear control that has been introduced in [Fliess et al., 2006a] and [Fliess et al., 2006b]. A first industrial and convincing application is reported in [Join et al., 2006].

2.1 Derivatives of noisy signals

Firstly, we recall basic of derivative estimation. Interested reader might refer to [Mboup et al., 2007] for a complete presentation.

Consider a real-valued time function x which is assumed to be analytic on some interval $t_1 \leq t \leq t_2$. For the sake of simplicity, assume x is analytic around $t = 0$ and introduce its truncated Taylor expansion:

$$x(t) = \sum_{\nu=0}^N x^{(\nu)}(0) \frac{t^\nu}{\nu!} + o(t^N)$$

Approximate $x(t)$ in the interval $[0, \varepsilon]$, $\varepsilon > 0$, by a polynomial $x_N(t) = \sum_{\nu=0}^N x^{(\nu)}(0) \frac{t^\nu}{\nu!}$ of degree N . The usual rules of symbolic calculus in Schwartz’s distributions theory yields

$$x_N^{(N+1)}(t) = x(0)\delta^{(N)} + \dot{x}(0)\delta^{(N-1)} + \dots + x^{(N)}(0)\delta$$

where δ is the Dirac measure at 0. From $t\delta = 0$, $t\delta^{(\alpha)} = -\alpha\delta^{(\alpha-1)}$, $\alpha \geq 1$, we obtain the following triangular system of linear equations for determining estimated values $[x^{(\nu)}(0)]_e$ of the derivatives¹ $x^{(\nu)}(0)$:

¹ Those quantities are *linearly identifiable* Fliess and Sira-Ramirez [2003].

$$\begin{aligned} t^\alpha x^{(N+1)}(t) &= t^\alpha \left([x(0)]_e \delta^{(N)} \right. \\ &\quad \left. + [\dot{x}(0)]_e \delta^{(N-1)} + \dots + [x^{(N)}(0)]_e \delta \right) \\ \alpha &= 0, \dots, N \end{aligned} \quad (1)$$

The time derivatives of x and the Dirac measures and its derivatives are removed by integrating with respect to time both sides of equation (1) at least N times:

$$\begin{aligned} \int^{(\nu)} \tau_1^\alpha x^{(N+1)}(\tau_1) &= \int^{(\nu)} \tau_1^\alpha \left([x(0)]_e \delta^{(N)} \right. \\ &\quad \left. + [\dot{x}(0)]_e \delta^{(N-1)} + \dots + [x^{(N)}(0)]_e \delta \right) \\ \nu &\geq N, \alpha = 0, \dots, N \end{aligned}$$

where $\int^{(\nu)} = \int_0^t \int_0^{\tau_{\nu-1}} \dots \int_0^{\tau_1}$ is an iterated integral. A quite accurate value of the estimates may be obtained with a small time window $[0, t]$.

2.2 Nonlinear systems

Consider the generalised state representation of a MIMO (multi-inputs multi-outputs) nonlinear system

$$\begin{aligned} A_\iota(\dot{x}_\iota, \mathbf{x}, \mathbf{u}, \dots, \mathbf{u}^{(\alpha)}) &= 0 \\ B_\kappa(y_\kappa, \mathbf{x}, \mathbf{u}, \dots, \mathbf{u}^{(\beta)}) &= 0 \end{aligned}$$

where A_ι , $\iota = 1, \dots, n$, B_κ , $\kappa = 1, \dots, p$, are nonlinear functions, $\mathbf{x} = (x_1, \dots, x_n)$ the state vector, $\mathbf{u} = (u_1, \dots, u_m)$ the input control vector, $\mathbf{y} = (y_1, \dots, y_p)$ the output (or measured signals) vector.

It exists a set of nonlinear functions Φ_j , $j = 1, \dots, p$, generally called input-output representation

$$\Phi_j(\mathbf{y}, \dots, \mathbf{y}^{(\bar{N}_j)}, \mathbf{u}, \dots, \mathbf{u}^{(\bar{M}_j)}) = 0 \quad (2)$$

with appropriate orders \bar{N}_j , \bar{M}_j .

2.3 Local model

We now introduce a local non physical model on which the model-free control will be developed in the next Section.

$$\begin{aligned} y_1^{(n_1)} &= F_1 + \alpha_{1,1}u_1 + \dots + \alpha_{1,m}u_m + \beta_1 \\ &\vdots \\ y_p^{(n_p)} &= F_p + \alpha_{p,1}u_1 + \dots + \alpha_{p,m}u_m + \beta_p \end{aligned} \quad (3)$$

where,

- $\bar{N}_j \geq n_j \geq 1$, $j = 1, \dots, p$;
- F_j , $\alpha_{j,i}$, $\beta_j \in \mathbb{R}$, $i = 1, \dots, m$, $j = 1, \dots, p$, are non-physical constant parameters free of choice;
- if $p > m$, m outputs are selected to insure invertibility property, i.e.

$$\det \gamma = \begin{pmatrix} \alpha_{1,1} & \dots & \alpha_{1,m} \\ \vdots & \ddots & \vdots \\ \alpha_{m,1} & \dots & \alpha_{m,m} \end{pmatrix} \quad (4)$$

To realise previous choices, some practical remarks are now given. They can be viewed like facilitating the implementation but not as restriction cases.

Remark 2.1. The smaller the integers n_j in (3) are, the better it is for the usefulness of the local model.

Remark 2.2. It is better to have as many zeros as possible on each row of the matrix γ .

Remark 2.3. The lower the orders of derivation of u are in Φ_j in (2), the better it is for the local model.

Here, we do not search to estimate F_j according physical knowledge but rather than totally unknown.

Thus, using derivative estimation $[y_j^{(n_j)}]_e$ of $y_j^{(n_j)}$ we obtain the explicit estimation of F_j

$$[F_j(t)]_e = [y_j^{(n_j)}]_e - \sum_{i=1}^m \alpha_{j,i} u_i - \beta_j \quad (5)$$

where all signals are known as constants.

To avoid algebraic loop and since numerical controller implementation are sampled

$$[F_j(\kappa)]_e = [y_j^{(n_j)}(\kappa)]_e - \sum_{i=1}^m \alpha_{j,i} u_i(\kappa - 1) - \beta_j$$

where $[\bullet](\kappa)_e$ stands for an estimation at time κ .

To conclude, let us insist on the fact that we use a local model estimated at each sampled time and none model structure is particularly considered. Indeed, function of time F_j is unspecified, i.e., without particularity.

2.4 Model-free control design

According to previous estimation, control law is divided into two parts,

$$\mathbf{u} = \mathbf{u}_p + \mathbf{u}_{\text{flat}}$$

where \mathbf{u}_p rejects the estimated model part which can be viewed as a model perturbation and \mathbf{u}_{flat} is classical flatness-based control (see, e.g., Fliess et al. [1995], Hagenmeyer and Delaleau [2003b,a]). At the last part is also associated a GPI (see Fliess et al. [2002]).

Model perturbation can be rejected thanks to

$$\mathbf{u}_p(\kappa) = - \begin{pmatrix} \alpha_{1,1} & \cdots & \alpha_{1,m} \\ \vdots & \ddots & \vdots \\ \alpha_{m,1} & \cdots & \alpha_{m,m} \end{pmatrix}^{-1} \begin{pmatrix} [F_1(\kappa)]_e + \beta_1 \\ \vdots \\ [F_m(\kappa)]_e + \beta_m \end{pmatrix}$$

Using this part of control (3) is rewritten

$$\begin{pmatrix} y_1^{(n_1)} \\ \vdots \\ y_p^{(n_p)} \end{pmatrix} = \begin{pmatrix} \alpha_{1,1} & \cdots & \alpha_{1,m} \\ \vdots & \ddots & \vdots \\ \alpha_{m,1} & \cdots & \alpha_{m,m} \end{pmatrix} \mathbf{u}_{\text{flat}} \quad (6)$$

One possibility is then to set

$$\mathbf{u}_{\text{flat}} = \begin{pmatrix} \alpha_{1,1} & \cdots & \alpha_{1,m} \\ \vdots & \ddots & \vdots \\ \alpha_{m,1} & \cdots & \alpha_{m,m} \end{pmatrix}^{-1} \begin{pmatrix} y_1^{*(n_1)} \\ \vdots \\ y_p^{*(n_p)} \end{pmatrix} + \begin{pmatrix} \delta_1 & 0 & \cdots & 0 \\ 0 & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & \delta_m \end{pmatrix} \begin{pmatrix} y_1^{(n_1)} - y_1^{*(n_1)} \\ \vdots \\ y_p^{(n_p)} - y_p^{*(n_p)} \end{pmatrix}$$

where y_i^* is the reference trajectory that must be tracked by y_i . The diagonal matrix $\delta = \text{diag}(\delta_1, \dots, \delta_m)$ is composed by rational function of polynomial in undetermined s such that all transfer functions $s^{n_i} - \delta(s)$ are stable. It ensures to reject estimation error of F_j and that tracking error decreases to zero.

3. CONTROL OF THE SMA ANTAGONISTIC ACTUATOR

Note that in this paper, the system model is important to ensure realistic simulations. Moreover due to his model complexity, SMA Antagonistic Actuator is a relevant example.

However, in a practical way, interest of the previous control strategy is to forgive the following section.

3.1 Model of SMA Antagonistic Actuator

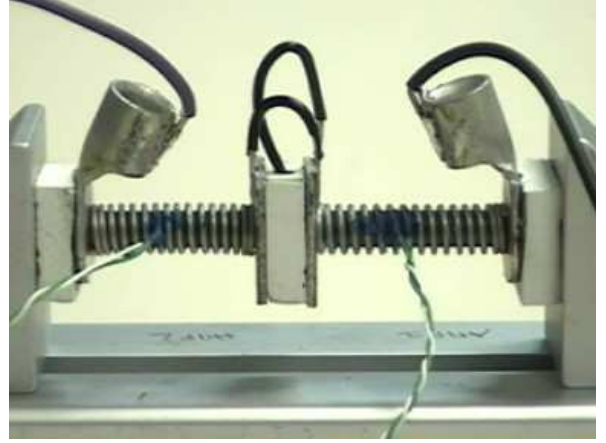


Fig. 1. Picture of the SMA Antagonistic Actuator

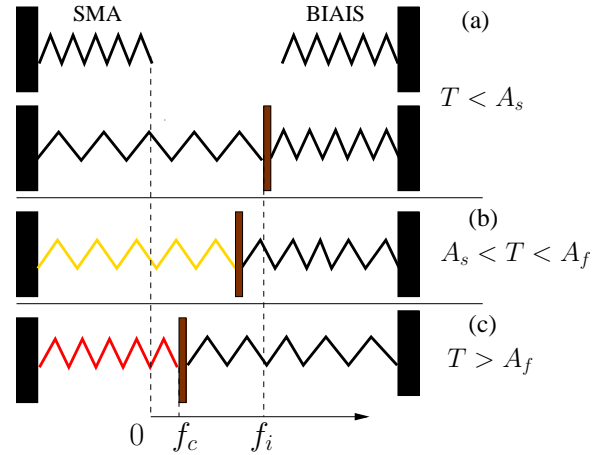


Fig. 2. Notations for the SMA spring actuator

We consider an actuator which consists of a SMA spring and a bias spring as in Fig. 1. The mechanism of this kind of actuator is decomposed into three steps. Firstly, when the temperature is constant and lower than the austenite start temperature A_s , the SMA spring is purely martensitic and the tensile force provided by the bias spring deforms the SMA spring to an initial deflection denoted by f_i , on Fig. 2-(a). Secondly the spring is heated by Joule effect, see Fig. 2-(b). To describe the evolution of the temperature as a function of the input electric power, we use equation (7) which is the simplified heat transfer equation proposed in Madill and Wang [1998].

$$\frac{dT}{dt} = -\frac{T - T_e}{\tau} + \frac{P}{mC} \quad (7)$$

Where P is the control input and corresponds to the electric power crossing the SMA spring, τ is the characteristic time of the SMA spring, m the mass of the spring, T_e the ambient temperature and C the specific heat of the SMA spring. When the temperature of the SMA spring goes past A_s , the martensite begins to change into austenite, so the spring tries to achieve his high temperature shape, during this phase we proposed to describe the deflection of the SMA spring as a function of the temperature as Fig. 3. This leads to a nonlinear control model.

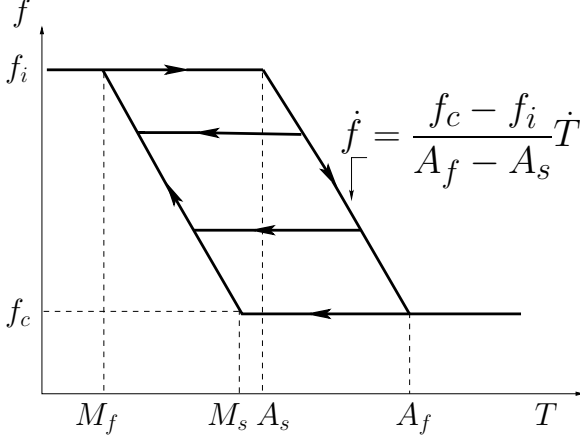


Fig. 3. Deflection-temperature hysteresis

When the temperature goes past the austenite finish temperature A_f , the persisted deflection denoted by f_c , on Fig. 2-(c), corresponds to austenite elasticity. Finally, when the spring is cooled lower than the martensite start temperature M_s (by free convection for example), the austenite changes into martensite and the effort provided by the bias spring permits the SMA spring to recover its low temperature shape. When the temperature reach the martensite finish temperature M_f , the spring is purely martensitic and the deflection reach the initial deflection f_i .

3.2 Control development

For this example the very simple first-order local model

$$\dot{y} = F + \alpha u$$

is considered. Here, we choose $\alpha = 0.5$ and at u corresponds the electric power crossing the SMA spring (P).

$$u = \frac{1}{\alpha} \left(-[F(\kappa)]_e + \dot{y}^* + K_p(y - y^*) + K_I \int (y - y^*) \right)$$

where K_p and K_I ensures that $s - K_p - \frac{K_I}{s}$ is stable transfer function.

3.3 Numerical simulations

Simulation parameters are given table 1.

Several simulation scenarios are considered. For each, figures 4 to 9, we present estimation needed to compute the control at each time :

- output derivative, computed in presence of an uniform noise in $[-0.05, 0.05]$,
- estimation of local model according F ,

- temperature evolution,
- control input u ,
- output tracking.

Scenario 1 (figure 4):

We present classical tracking. Note that our results can be favourably compared with results which would be obtained using exact knowing of model.

Scenario 2 (figure 5):

To test approach robustness, an abrupt change of T is simulated by the addition of bias of magnitude equals to -10°C (see figure 5-(c)). Control rejects easily this perturbation.

Scenario 3 (figure 6):

Another type of perturbation is simulated. At time $t = 50\text{s}$, τ change from 60 to 120. One more time, this important parametric change does not affect tracking trajectory. Model based control can be significantly corrupted.

Scenario 4 and 5 (figures 7 and 8):

Firstly, position decreasing satisfactorily thanks to a rather fast natural cooling. Secondly, the problem is getting more difficult to solve if the ambient temperature would be a little bit larger. This would slow the cooling effect. In this context, the eventual negative saturation of the control could be handled with a classical anti-windup devices added in the controller (see, e.g., Hippe [2006]).

Scenario 6 (figures 9):

To conclude, we change the trajectory profile and we want now a very fast respond. Control gives still waited results.

4. CONCLUSION

The contribution of the paper is twofold: Firstly, it presents a convincing application of the new free-model control in the area of SMA actuators control, a field in which control-model is especially difficult to obtain.

Secondly, in order to be able to present simulation results, the paper exposes a simplified model of the SMA Antagonistic Actuator. This model has been validated experimentally and works pretty well in situation where the behaviour is stabilised, i.e. is not varying along various thermomechanical cycles. However, in practise, the behaviour of SMA shows important hysteresis.

Parameter***	Value	Parameter**	Value
$Cm(\text{W}/^\circ\text{Cs})$	2.7×10^{-4}	$A_s(^\circ\text{C})$	42
$\tau(\text{s})$	60	$A_f(^\circ\text{C})$	75
Parameter*	Value	Parameter**	Value
$f_i(\text{mm})$	7	$M_s(^\circ\text{C})$	53
$f_c(\text{mm})$	3.5	$M_f(^\circ\text{C})$	44

Table 1. Simulation parameters obtain from spring model (*) DSC measurements (**) and heating tests (***)

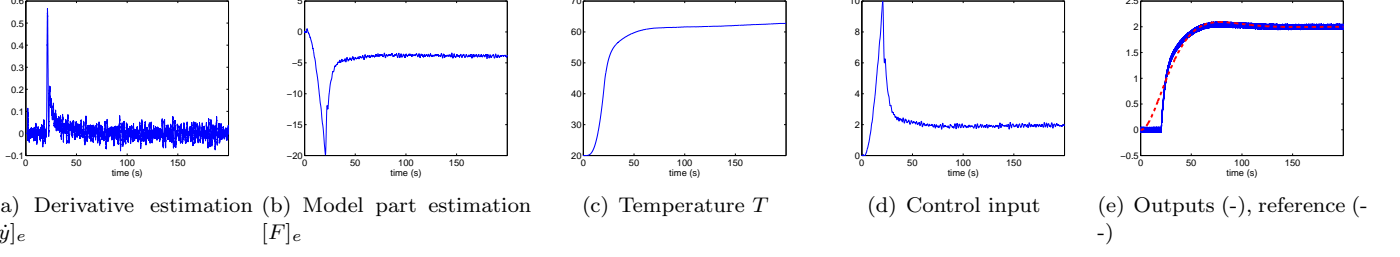


Fig. 4. Without perturbation

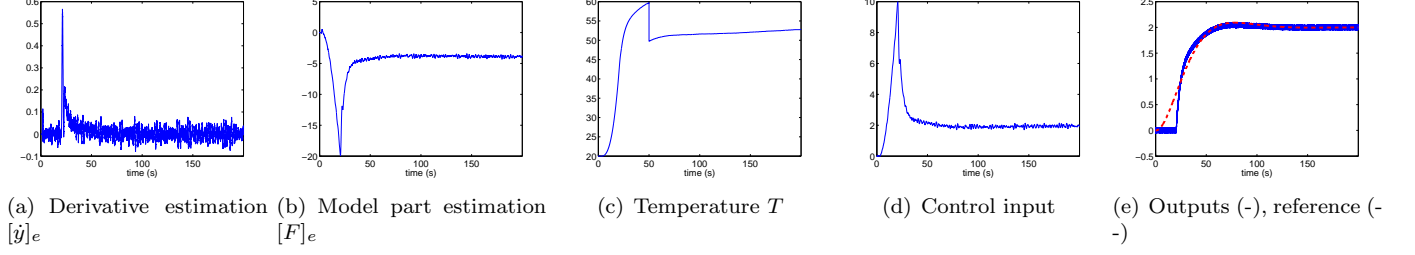


Fig. 5. Rejection of temperature perturbation

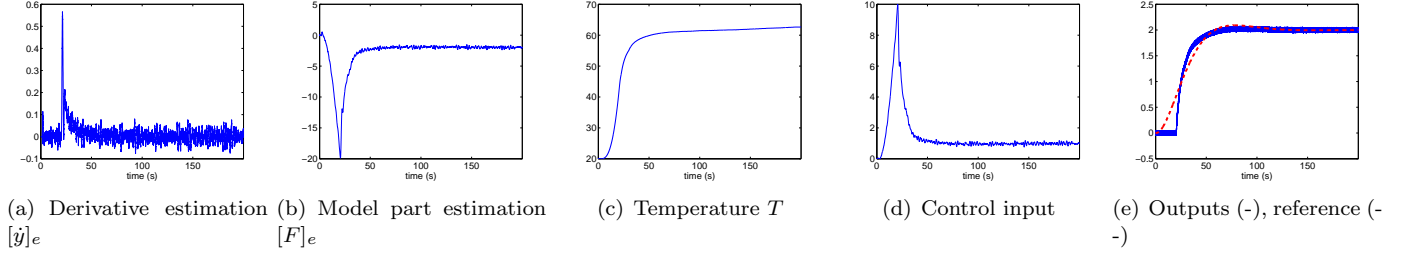


Fig. 6. Rejection of τ perturbation

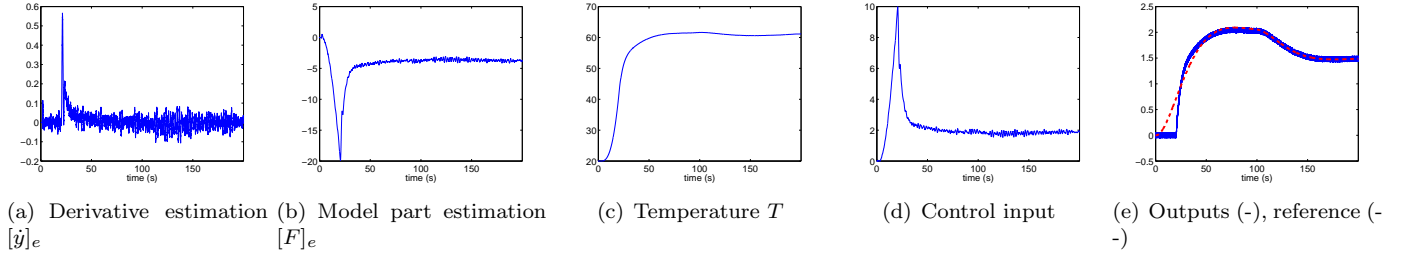


Fig. 7. Lower trajectory change

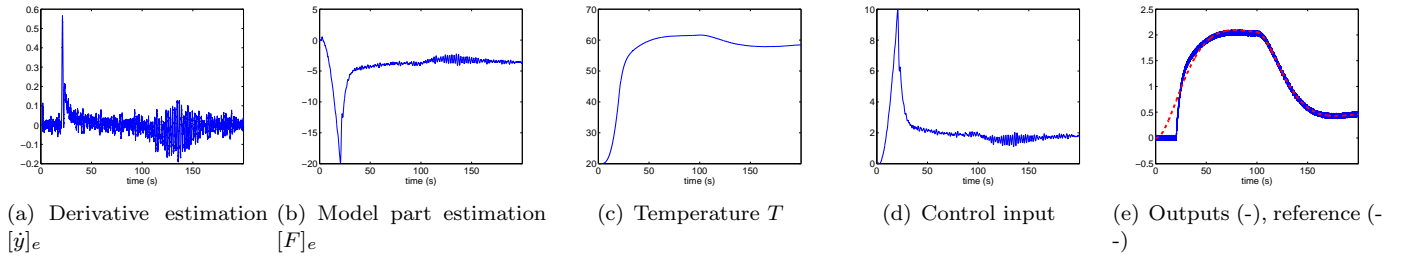


Fig. 8. Large trajectory change

We are very confident to be able to solve this problem and to show in a short time good experimental results using the model-free control in combination with on-line parameter estimation.

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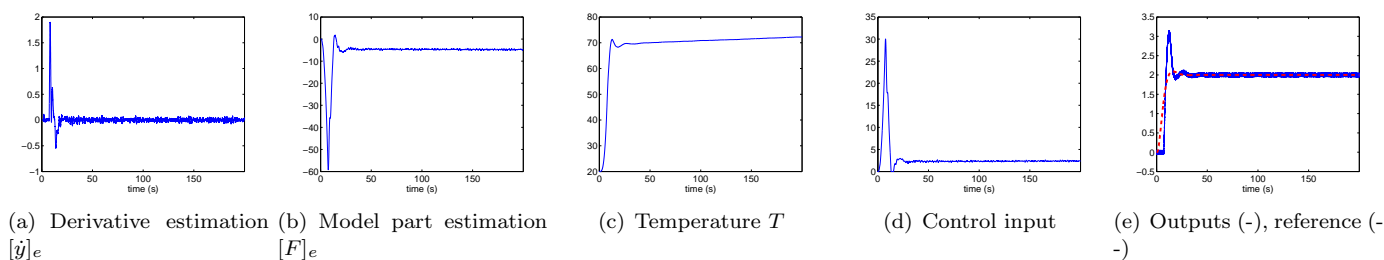


Fig. 9. Fast response

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